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Open Channel Flow Measurement of Water by Using Width Contraction

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***Abstract*—**Present study was aimed to develop a discharge measuring device for irrigation and laboratory channels. Experiments were conducted on sharp edged constricted flow meters having four types of width constrictions namely 2:1, 1.5:1, 1:1 and 90° in the direction of flow. These devices were made of MS sheets and installed separately in a rectangular flume. All these four devices were tested under free and submerged flow conditions. Eight different discharges varying from 2 lit/sec to 30 lit/sec were passed through each device. In total around 500 observations of upstream and downstream depths were taken in the present work. For each discharge, free submerged and critical submergence under different flow conditions were noted and plotted. Once the upstream and downstream depths of flow over any of the device are known, the discharge can be easily calculated with the help of the curves developed for free and submerged flow conditions. The device having contraction 2:1 is the most efficient one as it allows maximum critical submergence.

***Keywords*—**Flowrate, flowmeter, open channels, submergence.

I. INTRODUCTION

WATER resources play a significant role in the national development & constitute a critical input for economic planning in the developing countries like India. Due to rapid industrialization, agricultural development and population explosion, availability of good quality water has become scarce and in short supply. The basic understanding of measurement of the discharge in open channel is essential for efficient management and development of water resources projects. Flumes form the backbone of water measurement networks for open channel irrigation and drainage systems. A precise and uniform method of discharge measurement is must for various projects like irrigation, farming, water supply, flood control & power generation etc. The important points considered before selecting any technique or method for discharge measurement in open channels are capital investment, discharge range, long term & short term record, degree of accuracy, physical geometry of the channels, afflux, accessibility of site, sediment deposition, installation etc. Flowrate in the open channels can be measured by using various devices and direct methods like weirs, flumes, dilution techniques, velocity area method, slope hydraulic area method and mathematical models etc. as mentioned by [1]-[6].

A. Various Gauging Structures

Main categories of gauging structures which are frequently used for flow measurement in open channels are described below [3].

1. Thin Plate Devices

These devices are made of metal plates which are installed vertically with an accurately machines upstream edge of thickness not exceeding 2 mm and a bevel of angel 45° to the downstream edge. The various geometrical shapes of sharp-crested weirs are rectangular, triangular, trapezoidal, parabolic, proportional etc. These are used as flow measuring devices in the laboratory, industries and irrigation practices. The estimation of discharge (Q) can be done by the following relation $Q = K h^n$ where K is a constant and h is upstream head and n is the exponent of head over weir.

2. Long Base Weir

These weirs are generally made of concrete/masonry having foundation or base which is comparatively much longer in the direction of flow. These weirs are classified as broad crested weir and short crested weir depending upon the width of crest with respect to upstream head.

3. Flumes

Flumes are especially designed, shaped, fixed hydraulic structures those under free flow conditions force the flow to accelerate in such a way that flow may be characterized by a known relationship between head at specific location and the flowrate. Acceleration is provided by converting the side walls, raising the bottom floor or a combination of both. These are critical open channels made of precast concrete masonry, timber, glass fiber etc. depending upon the location & the functional requirements which may be supported on or above the ground level to transport water. Flumes are one of the most commonly used devices for flow measurement in open channels. Advantages of flume over a weir are that the head loss in flume is ¼ th of the weir for same width of weir, and velocity of approach is a part of the calibrated equation in the flume. These are classified as Venturi flumes, Standing wave flumes, Cut throat and Parshall flumes, venturi flumes as proposed by [1], [7], [8]. The Parshall flumes are suited to be installed in the channel without much of afflux and can allow sediments to pass but their calibration is not easy. But they are having a complex geometry and the Parshall flumes of different sizes are not geometrically similar. The discharge can be found out using calibration charts / curves given specifically for each size. The discharge is also affected by submergence. The flow device using semi-circular cylinders

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on either side of a rectangular flume, developed by [9] can be a solution. References [10], [11] also proposed a simple constricted width flowmeter for flow measurement in open channels, which is geometrically similar and easy in construction and use. A sharp crested width constriction device also suggested with straight boundaries having a contraction and a drop was tested and suggested for irrigation channels in the past [12].

II. Past Studies on Constricted Width Flow Meters

A constricted width flowmeter having two types of inlet transitions such as plane and circular type has been evolved in past by [10]. A flowmeter with plane inlet transition was used in a rectangular channel having a slope of 2 in 1 at the inlet transition portion. After this, a throat of length equal to 1 b (b = throat width of the flow meter) was provided. The total length of the device was equal width of the channel (B) having constriction at throat equal to 50%. The front half portion of the device was made circular with a radius equal to b/2. The total length of the flowmeter was equal to half of the width of the channel. The device is geometrically similar and simple having more field applications. A new type of flow meter having different constriction ration b/B equal to 0.4, 0.5, and 0.6 without any upstream and downstream transitions in the past [13]. These devices have got better application for lower b/h_u ratios. The flowmeter is simple and easy in construction with more practical applications.

The flowmeter recommended by [10] has to be constructed in masonry and has more length due to upstream transition. The sharp edged constricted flowmeter suggested by [13] has a sudden contraction and expansion of flow without proper transition. This may cause more head loss if b/B is less than 0.5. There is more obstruction to flow, which may create more afflux there by requiring raising of banks.

III. Scope and Objectives of Present Study

Most of the available critical depth flumes are not easy to construct and quite expensive due to their larger lengths. The critical flumes like Parshall flumes are not geometrically similar because their sizes and dimensions vary with the change in discharge. There is a large variation in the coefficient of discharge in such flumes. In case of weirs, there is a problem of sediment deposition on upstream size and heading up of water on upstream side which will further increase the cost. Keeping in mind the various limitations of critical depth flumes, a new type of flowmeter is being investigated to measure discharge in open channels. It is envisaged to be a simple in construction, easy in installation, shorter in length and of more practical utility. It is also expected that the performance of flowmeter is not affected by sediment movement & there will be no problem of increased afflux in respect of flooding or raising of the banks.

In the present study, a sharp edge constricted width flowmeter is used in which three slopes 2:1, 1.5:1, 1:1 and 90^o are provided in the downstream sides to avoid head loss. It is envisaged to be a simple device which is easy in construction, installation and maintenance free having more applications in laboratory and irrigation channels [14].

IV. Experimental Studies

The experiments were conducted in a 12 m long, 40 cm wide and 60 cm deep tilting bed flume in the Fluid Mechanics Laboratory of Regional Engineering College (NIT) Kurukshetra. There were three panels of glass for visual observation and rests of the panels were made of steel plates on both sides. It was supported on a steel truss with a jack for the adjustment of the bed slope. The water pumped from a sump channel with the help of a 15 HP centrifugal pump which is discharging into a stilling tank upstream of the flume. A pair of baffle plates was provided to dampen the disturbances caused by the water in the flow. Two floating wooden planks were also used in the flume to dampen the turbulence in the flow further downstream direction. A tailgate was provided at the end of the flume to control the depth of flow. Water after passing through the flume goes to a rectangular tank. The outlet channel from the concrete tank passes the flow over the sharp crested weir of height 40 cm provided in a 60 cm wide channel to measure the discharge downstream before entering to the sump channel. The proposed constricted width flowmeter (2:1,1.5:1,1:1 and 90^o) was fitted in the best section of flume so that sufficient upstream and downstream lengths of channel are available for proper development of flow. One 40 cm high sharp crested weir without end contraction was prepared using 6 mm thick M.S. plates. This weir was used in the downstream of steel flume in a 60 cm wide masonry downstream channel to measure the discharge. The head over weir was noted for any inflow in the flume by using a pointer gauge. Proper ventilation of the weir was also ensured. The schematic diagram of experimental set up has been shown in Fig. 1.

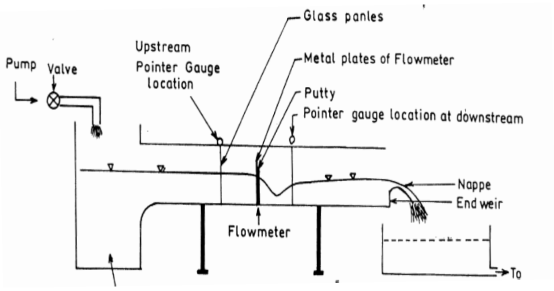
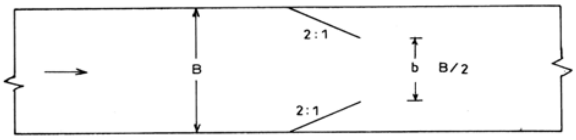


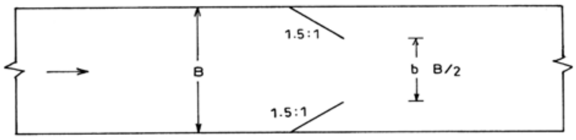
Fig. 1 Experimental set up

A. Description of Constricted Width Flowmeter

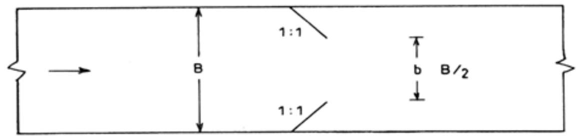
The M.S. Sheets (3 mm thickness) were used for fabricating the required constricted width flowmeters. Each flowmeter consisted of two metal plates of equal dimensions placed opposite to each other on either sides of the flume. In each flowmeter, the width at throat was reduced by 50% i.e. b/B = 0.5. For fixing metal plates in the flume, glass putty was applied on the back sides and bottom of the plates in the backward direction to avoid any possible disturbance to the incoming flow. Both the edges of the plate in the direction of flow at the constriction were sharpened by 45° to avoid frictional losses. Four different flowmeters having contraction 2:1, 1.5:1, 1:1 and 90° were used separately inside the flume. The details of flowmeters tested along with their details are as shown in Fig. 2.



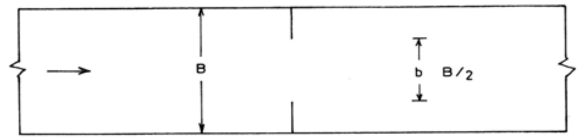
(a) Contraction 2:1



(b) Contraction 1.5:1



(c) Contraction 1:1



(d) Contraction 90°

Fig. 2 (a)-(d) Definition sketch of sharp crested flowmeters (width constriction 2:1, 1.5:1, 1:1 and 90°)

TABLE I
SCHEME OF EXPERIMENTATION

Type of flowmeter with contraction	No. of Sets	No of observations	Discharge Range (m^3/sec)
2:1	8	54	2.3 to 30.50 x 10^{-3}
1.5:1	8	55	3.05 to 27.89 x 10^{-3}
1:1	8	56	2.06 to 25.07 x 10^{-3}
90°	8	58	2.48 to 30.50 x 10^{-3}

B. Experimental Procedure

After proper priming, centrifugal pump was started and inlet valve to the flume for flow of water is opened. The flow was allowed to get steady & uniform and later on stabilized for reasonable period of time. Two pointer gauges were used for measurement of depth of flow at upstream and downstream of the flowmeter installed in the flume.

In the beginning, the tail gate was completely opened for observing upstream head for free flow condition and then gate was gradually lowered in stages and downstream and upstream flow depths were recorded simultaneously. Again tail gate was further lowered and upstream and downstream heads were noted. It was observed that at a particular downstream flow depth, the upstream flow depth starts increasing. This stage of flow in flume is called critical submergence. Repeatability tests were also conducted to check and ensure the accuracy in measurement covering the range of discharge. This procedure was repeated for three other constriction ratios also. The scheme of experimentation along with range of discharges used during the study for each type of flowmeter of all the four types of flowmeter is mentioned in Table I.

V. DISCUSSIONS

The discharge through a measuring flume in general will depend on the inlet and outlet transitions, throat width (b), acceleration due to gravity (g), upstream depth (h_u), downstream depth (h_d) and fluid characteristics. But when inlet and outlet transitions are short and flow takes place at high Reynolds number for flumes, the following equation for a weir may be assumed.

$$Q = K\, b\, \sqrt{2g}\, h_u^{3/2} \qquad (1)$$

Assuming coefficient of the discharge (K) is a function of non-dimensional parameters h_d/h_u and b/h_u for the present flowmeter as $K = f\,(h_d/h_u,\ b/h_u)$. The loss of head on upstream of throat is considered to be small and loss of head downstream will be governed by the geometry like an expansion under submerged conditions and due to a hydraulic jump under free conditions.

The data for all the four types of constricted width flowmeter having contractions 2:1, 1.5:1, 1:1 and 90° for free and submerged flow were collected separately. The values of coefficient of discharge (K) and submergence ratios h_d/h_u were calculated for free and submerged flow conditions and results are analyzed in the following paragraphs.

A. Free Flow Conditions

It was observed that for any discharge condition, the upstream depth (h_u) remain unaffected as long as the submergence ratio (h_d/h_u) is less than the critical submergence for any of the four devices tested. In those situations, the flow is said to be free flow. By using the data for free flow conditions, a graph between K and b/h_u values using (1) for all the four devices is plotted as shown in Fig. 3. It is clear from Fig. 3 that as the b/h_u value increases, the value of K reduces. It also indicates that with the increase in the discharge, the value of K increases upto b/h_u equal to one. For any constant value of b/h_u, the value of K is maximum for contraction 2:1 where as it minimum for contraction 90°. It is quite evident from Fig. 3 that in gradual contraction flowmeter i.e. 2:1 type, the head losses are much less as compared to sudden contraction flowmeters such as 1.5:1, 1:1 and 90°. These losses are maximum in case of sudden contraction case of 90° due to obvious reasons.

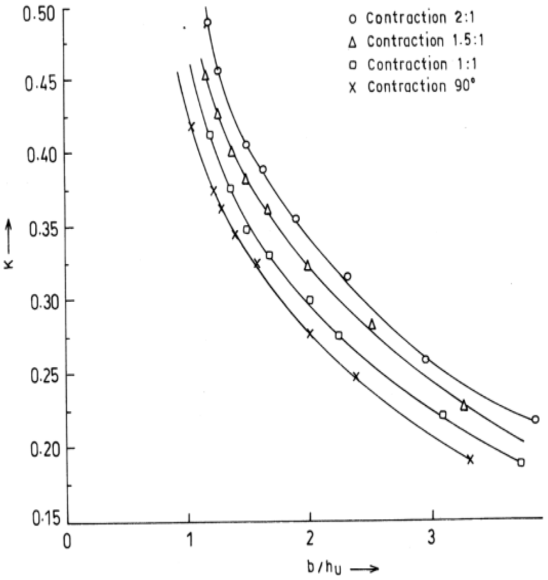


Fig. 3 Plotted curves for different contraction ratios of flowmeters under free flow conditions

B. Submerged Flow Conditions

An important feature of the operation of critical depth flume is its non- sensitivity to the change in tail water and its effect on discharge estimation. A real and practical flowmeter should be able to tolerate large depths of downstream flow without affecting the upstream depth of flow. When increase in the downstream depth of flow from the flume, just starts increasing in the upstream head of the flume than the critical depth flume is said to be operating at modular limit or critical submergence limit. The critical submergence has been expressed in terms of submergence ratio equal to h_d/h_u in present setup. The downstream level at which the critical submergence is attained depends on the energy loss in the expansion which is the crucial factor in determining the critical submergence in any critical depth flume or flowmeter [3]. In the submerged flow conditions, the downstream depth is increased by closing the tail water depth gradually. In such situation, the discharge can be calculated by the following relation

$$Q = K\, b\sqrt{2g}\, h_{us}^{3/2} \tag{2}$$

where h_{us} is upstream depth of flow under submerged flow conditions. The values of h_d/h_{us} are also calculated along with K in submerged flow conditions. The data of b/h_{us} and K for each flowmeter along with h_d/h_{us} for four shapes of flowmeter 2:1,1.5:1,1:1 and 90° as per scheme of experimentation (Table I) for free and submerged flow conditions were collected. Under submerged flow conditions, on each graph a free flow curve of the corresponding flow meter is also plotted for all the four types of flowmeter. By interpolating between two consecutive submergence ratios, the points of h_d/h_{us} = 0.6, 0.65, 0.7, 0.75, 0,8, 0.85 and 0.9 are marked and joined with smooth curve by judgment for four shapes of flowmeter 2:1,1.5:1,1:1 as shown in Figs. 4-7 respectively. Whenever any submergence curve meets the free flow curve, it indicates the critical submergence. When the contraction is gradual, the critical submergence occurs at higher value such as in case of 2:1 contraction flowmeter. But this effect diminishes with the increase in discharges. For higher range, the contraction in the sloping form of flowmeter is better in comparison to 90° contraction.

The values of critical submergence for all the four flowmeter with different discharges are noted and are given in Table II. Perusal of Table II states that the values of critical submergence are maximum for contraction 2:1 and minimum for contraction 1:1. It is due to the fact that the flow at the entrance is evenly distributed and the energy losses are minimum in case of contraction 2:1 which permits higher critical submergence. It further means that the flowmeter of contraction 2:1 is more useful than the other contraction flowmeters of 1.5:1, 1:1 and 90°. The values of K for all four configurations 2:1, 1.5:1, 1:1 and 90° for different submergence ratios h_d/h_{us} are noted for an arbitrary value of b/h_{us} from Figs. 4-7 and are mentioned in Table III. The examination of Table III indicates that the value of coefficient of discharge (K) is maximum for 2:1 width contraction ratio as compared to remaining three configurations. It has become possible only due to smaller head losses taking place in the transition 2:1 as compared to other contraction ratios such as 1.5:1, 1:1 and 90°.

TABLE II
CRITICAL SUBMERGENCE OF FLOW METERS

Contraction 2:1		Contraction 1.5:1		Contraction 1:1		Contraction 90°	
h_d/h_{us}	K	h_d/h_{us}	K	h_d/h_{us}	K	h_d/h_{us}	K
0.90	0.15	0.90	0.14	0.90	-	0.90	-
0.85	0.22	0.85	0.19	0.85	0.13	0.85	0.12
0.80	0.24	0.80	0.23	0.80	0.18	0.80	0.17
0.75	0.28	0.75	0.27	0.75	0.23	0.75	0.21
0.70	0.32	0.70	0.31	0.70	0.28	0.70	0.24
0.65	0.34	0.65	0.32	0.65	0.29	0.65	0.26

TABLE III
VALUES OF K OF FLOW METERS FOR B/H_{US} = 2.0

Contraction 2:1		Contraction 1.5:1		Contraction 1:1		Contraction 90°	
Q x 10^{-3} m^3/sec	h_d/h_{us}	Q x 10^{-3} m^3/sec	h_d/h_{us}	Q x 10^{-3} m^3/sec	h_d/h_{us}	Q x 10^{-3} m^3/sec	h_d/h_{us}
2.30	0.63	3.05	0.57	2.06	0.53	2.48	0.59
3.95	0.64	6.06	0.61	3.20	0.55	5.32	0.62
7.00	0.69	9.10	0.70	6.50	0.61	7.68	0.68
10.62	0.72	13.71	0.71	8.33	0.62	12.93	0.68
14.68	0.74	16.71	0.72	12.34	0.68	16.20	0.69
17.77	0.75	19.65	0.75	15.14	0.71	19.76	0.71
25.33	0.76	23.44	0.76	19.49	0.73	21.81	0.71
30.50	0.78	27.89	0.76	25.07	0.75	30.50	0.74

VI. ESTIMATION OF DISCHARGE

Any one of these flowmeters having width constrictions 2:1, 1.5:1, 1:1 and 90° is installed in the open channel where discharge is to be measured as per the dimensions of the devices (Fig. 2). Under free flow conditions, for any value of discharge, the value of h_u is taken by pointer gauge or any other suitable system and corresponding b/h_u value is noted from Fig. 2. Now by using relation $Q = k\, b\, \sqrt{2g}\, h_u^{3/2}$ the discharge in the channel can be calculated for given value of throat width b (half of width of channel). Under submergence flow conditions, both values of h_{us} & h_d are noted. The value of K corresponding to value of b/h_{us} can be noted by using corresponding Figs. 4-7 depending upon type of flowmeter installed in the channel.

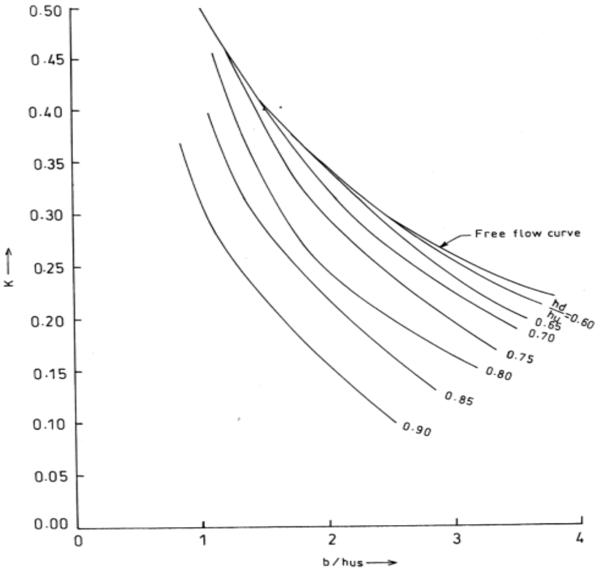


Fig. 4 Plotted curves for different submergence ratio for 2:1 flowmeter

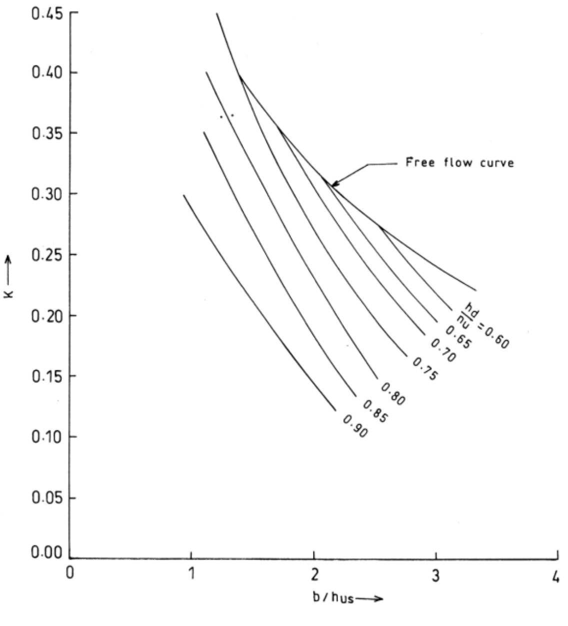


Fig. 5 Plotted curves for different submergence ratio for 1.5:1 flowmeter

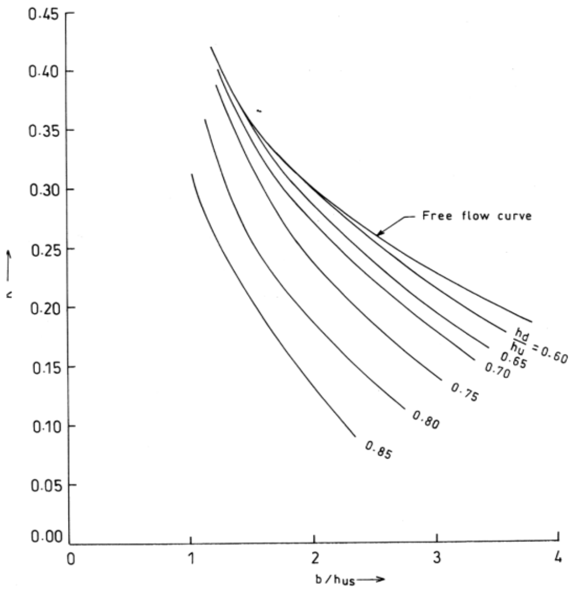


Fig. 6 Plotted curves for different submergence ratio for 1:1 flowmeter

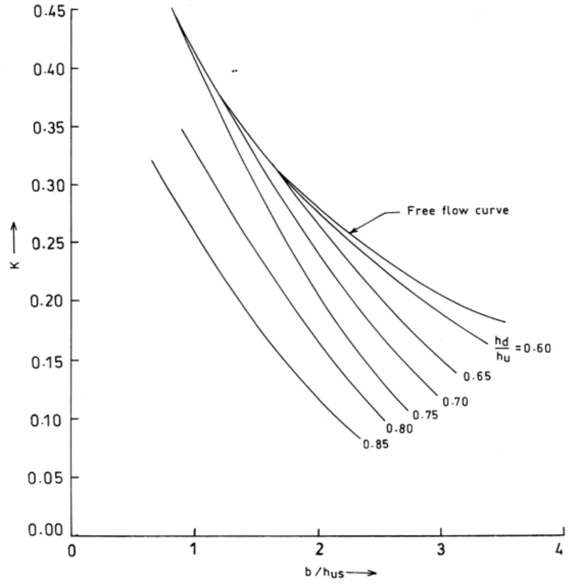


Fig. 7 Plotted curves for different submergence ratio for 90° flowmeter

Now taking these values of K & h_{us}, the discharge can be calculated by the following expression $Q = k\, b\, \sqrt{2g}\, h_{us}^{3/2}$. In other words, we can say that the proposed flowmeters having width constriction (2:1, 1.5:1, 1:1 and 90°) can be easily used for estimation of the discharge in the open channel correctly under free and submerged flow conditions. It has significant advantages over other traditional devices and requires minimum head loss to maintain critical flow conditions in the throat.

VII. CONCLUSIONS

Formulae and graphs required for estimation of discharge field under free and submerged flow conditions have been established for four types of constricted width flowmeter (2:1, 1.5:1, 1:1 and 90^o). Length of the proposed devices is much shorter than other conventional critical depth flumes and hence they have lesser cost of construction. Further proposed flowmeters have distinct advantages over other critical depth flume and weir devices due to ease in construction and installation. The discharge can be easily calculated under free and submerged flow conditions by using proposed graphs and equations without causing much afflux and head losses. However, flowmeter having 2:1 width transition can be used more efficiently and effectively up to a higher submergence limit for measurement of water in open channels.

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